Decoupling property of SUSY extended Higgs sectors and implication for electroweak baryogenesis

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S. K., T. Shindou, and K. Yagyu PLB699, 258 (2011)
M. Aoki, S.K., T. Shindou, K. Yagyu, arXiv: 1108.1356
S.K, E. Senaha, T. Shindou, arXiv:1109.5226

LCWS11, Granada, Sep.28, 2011

Higgs sector and New Physics

- SM has been successful
  - But, yet to be established
  - Higgs sector is unknown

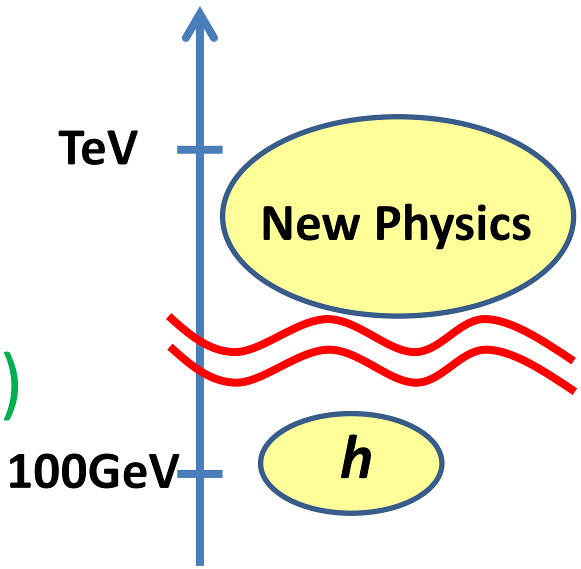
Possibility of a non-minimal Higgs sector

- Requirement for physics BSM
  - Hierarchy problem
  - Dark Matter
  - Neutrino mass
  - Baryon Asymmetry of Universe

We expect new physics BSM at the TeV scale

Higgs sector is the key to new physics

Decoupling/Non-decoupling



- Decoupling Theorem

  Appelquist-Carazzone 1975

  New phys. loop effect in observables

  $1/M^n \rightarrow 0$ (decouple for $M \rightarrow \infty$)

- Violation of the decoupling theorem
  - Chiral fermion loop (ex. Top, 4th gen.)

    $m_f = y_f v$
  - Boson loop (ex. H^+ in non-SUSY 2HDM)

    $m_\phi{}^2 = \lambda_i v^2 + M^2$ (when $\lambda v^2 > M^2$)

  Non-decoupling effect

Higgs potential

To understand the essence of EWSB, we must know the self-coupling in addition to the mass independently

$$\boxed{V_{\rm Higgs} = \frac{1}{2}\underline{m_h^2} h^2 + \frac{1}{3!}\underline{\lambda_{hhh}} h^3 + \frac{1}{4!}\lambda_{hhhh} h^4 + \cdots}$$

Effective potential

$$V_{\rm eff}(\varphi) = -\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{4}\varphi^4 + \sum_f \frac{(-1)^{2s_f} N_{C_f} N_{S_f}}{64\pi^2} m_f(\varphi)^4 \left[\ln\frac{m_f(\varphi)^2}{Q^2} - \frac{3}{2}\right]$$

Renormalization Conditions

$$\left.\frac{\partial V_{\rm eff}}{\partial\varphi}\right|_{\varphi=v} = 0, \quad \left.\frac{\partial^2 V_{\rm eff}}{\partial\varphi^2}\right|_{\varphi=v} = m_h^2, \quad \left.\frac{\partial^3 V_{\rm eff}}{\partial\varphi^3}\right|_{\varphi=v} = \lambda_{hhh}$$

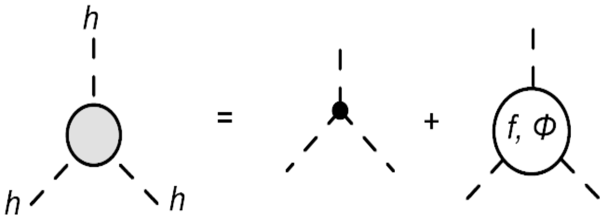
SM Case

$$\boxed{\lambda_{hhh}^{\rm SMloop} \sim \frac{3m_h^2}{v}\left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right)}$$

Non-decoupling effect

Case of Non-SUSY 2HDM

- Consider when the lightest *h* is SM-like [sin(β–α)=1]
- At tree, the *hhh* coupling takes the same form as in the SM
- At 1-loop, non-decoupling effect $m_\Phi{}^4$ (If $M < v$)



Φ = H, A, $H^\pm$

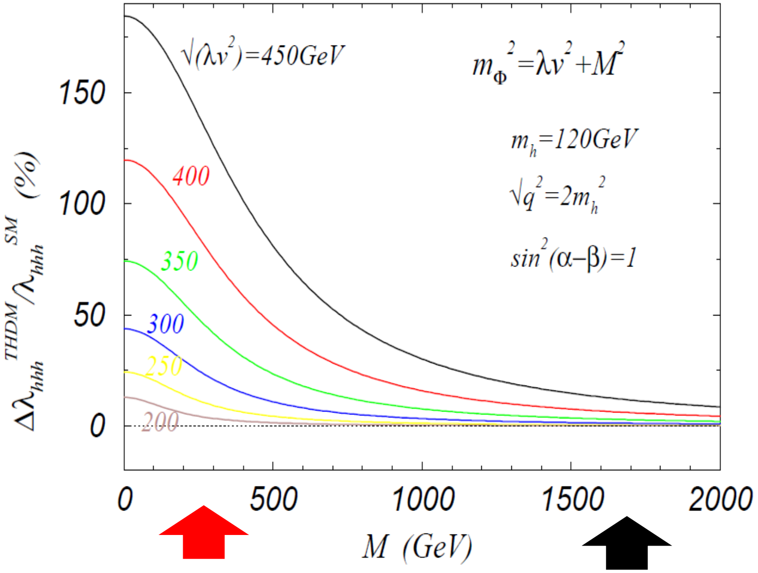
SK, Kiyoura, Okada, Senaha, Yuan, PLB558 (2003)

$$\boxed{\lambda_{hhh}^{2\mathrm{HDM}} \simeq \frac{3m_h^2}{v}\left[1+\underbrace{\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3}_{\text{Extra scalar loop}}-\underbrace{\frac{m_t^4}{\pi^2 v^2 m_h^2}}_{\text{Top loop}}\right]}$$

$$m_\Phi^2 = M^2 + \lambda_i v^2$$

(Φ = H, A, $H^\pm$)

Correction can be huge ～ 100%



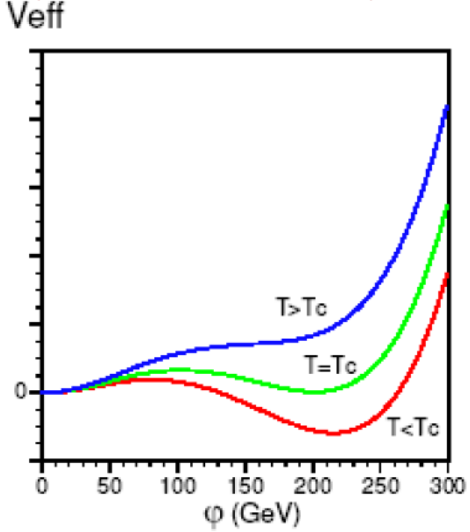
Non-decoupling effect

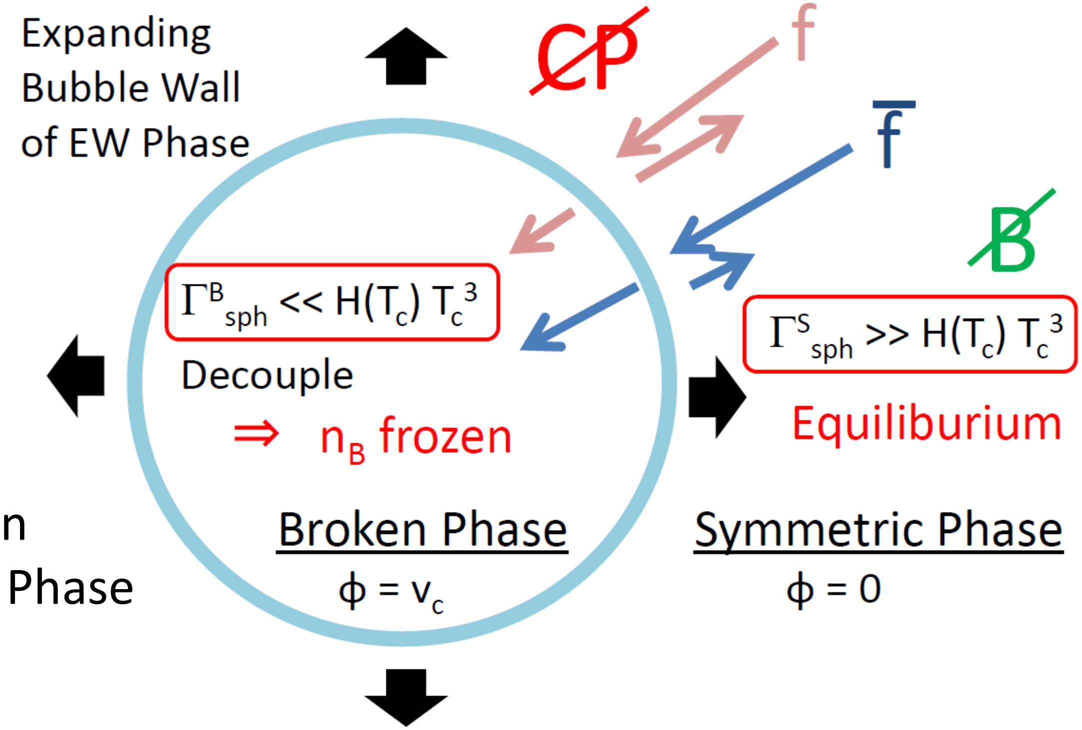
Decoupling

Relation to electroweak baryogenesis

Sakharov's conditions:

- B Violation → Sphaleron transition at high *T*
- C and CP Violation → CP Phases in extended scalar sector
- Departure from Equilibrium → 1^{st} Order EW Phase Transition





Expanding Bubble Wall of EW Phase

$\cancel{CP}$

$\cancel{B}$

$\Gamma^B_{sph} << H(T_c)\, T_c^3$

Decouple

⇒ n_B frozen

$\Gamma^S_{sph} >> H(T_c)\, T_c^3$

Equiliburium

Broken Phase

$\phi = v_c$

Symmetric Phase

$\phi = 0$

Quick sphaleron decoupling to retain sufficient baryon number in Broken Phase

$$\boxed{\frac{\varphi_c}{T_c} \gtrsim 1}$$

EW baryogenesis and the *hhh* coupling

Finite temperature potenital

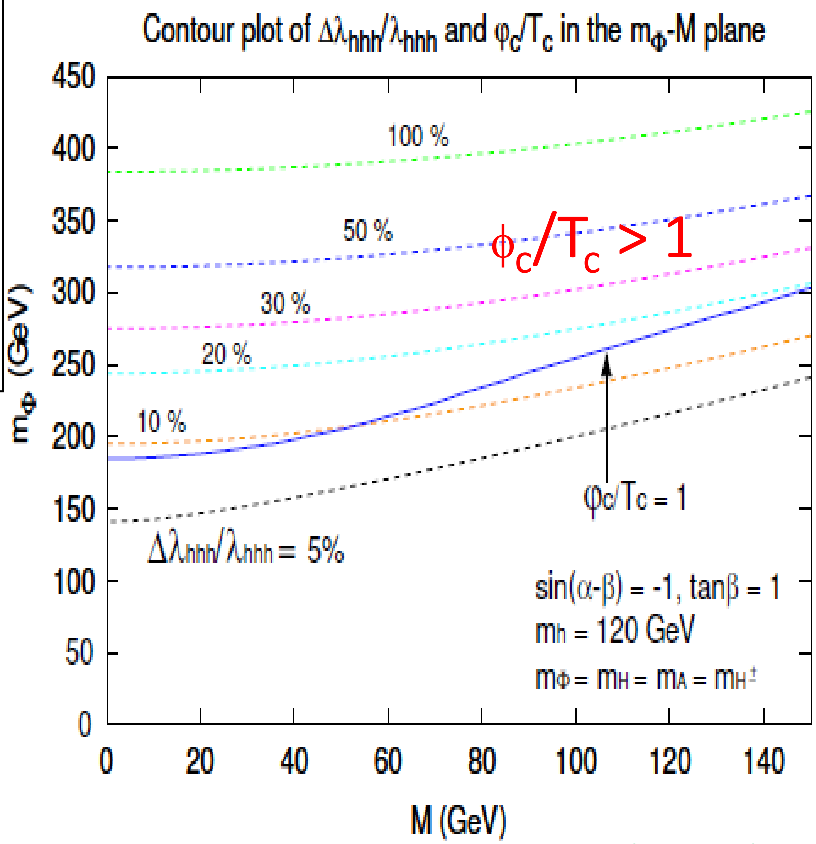
$$V_T(\phi,T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots..$$

$$\phi_c/T_c = 2E/\lambda_{T_c}$$

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$$ + New Phys. Effect

$$\lambda_T = m_h^2/2v^2 + \text{log corrections}$$

$$\boxed{\phi_c/T_c > 1 \Rightarrow 2E/\lambda_{T_c} > 1}$$



SK, Okada, Senaha (2005)

SM: $m_h < 60$GeV Excluded by LEP

2HDM: m_h = 120GeV Possible due to non-decoupling effect

Strong 1st OPT ⇔ Large *hhh* coupling

In this talk

- We consider an extended SUSY Higgs model which can realize the strong 1st OPT due to the non-decoupling effect
- SUSY
  - Cancellation of quadratic divergences
  - DM candidate (R-parity)
  - Many CP phases
  - GUT, Radiative EW breaking
  - Even if it becomes a strong coupled theory at 10 TeV, still nice

- EW baryogenesis in SUSY models

  MSSM, MSSM+U(1), NMSSM, ….

- We here consider a new model for EW baryogenesis

What kind of SUSY Higgs sectors give strong 1st OPT ?
(large deviation in the *hhh* coupling?)

Case of Non-SUSY THDM

$$\boxed{\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3-\frac{m_t^4}{\pi^2 v^2 m_h^2}\right]}$$

1. MSSM: only D term [+ (F-term top Yukawa at loop)] determines m_h , *hhh* etc. (A light stop scenario)

2. General SUSY Higgs sector

$V_{int} = |D|^2 + |F|^2 +$ Soft-breaking

F-term contributions: appear with additional singlets, triplets

$W = \lambda \quad H_u.H_d \, \varphi$

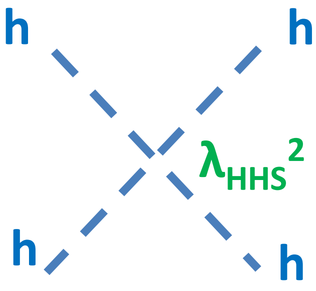
Large non-decoupling effects can appear in observables via F-term

NMSSM (MSSM＋S)

Chiral Superfield: **S (singlet)**
which generates F-term interaction

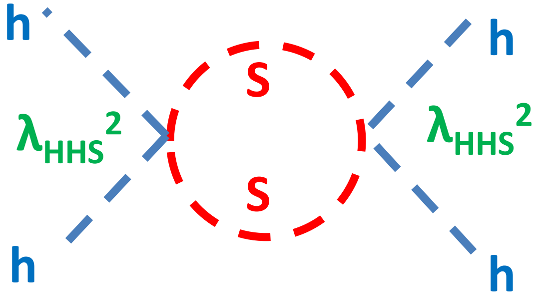
$$\boxed{W = \lambda_{HHS}\ H_u H_d S}$$

$$V_F = \lambda_{HHS}{}^2\ |H_u H_d|^2 + \lambda_{HHS}{}^2\ |H_u S|^2 + \lambda_{HH\phi}{}^2\ |H_d S|^2$$



Tree level
Contribution
To the mass

One-loop
Contribution to
The *hhh* coupling



Same coupling makes both m_h and the *hhh* coupling large

Fat Higgs model

Harnik, Kribs, Larson, Murayama

Composite H_1, H_2, N

A UV complete theory

At low energy, a strong NMSSM

$$W = \lambda(NH_1H_2 - v_0^2)$$

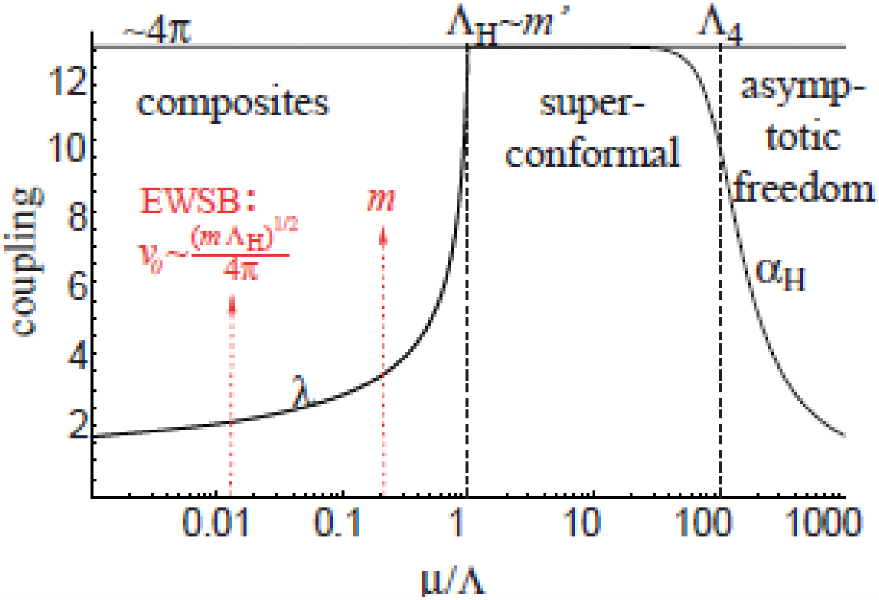
The SM-like Higgs can be heavy

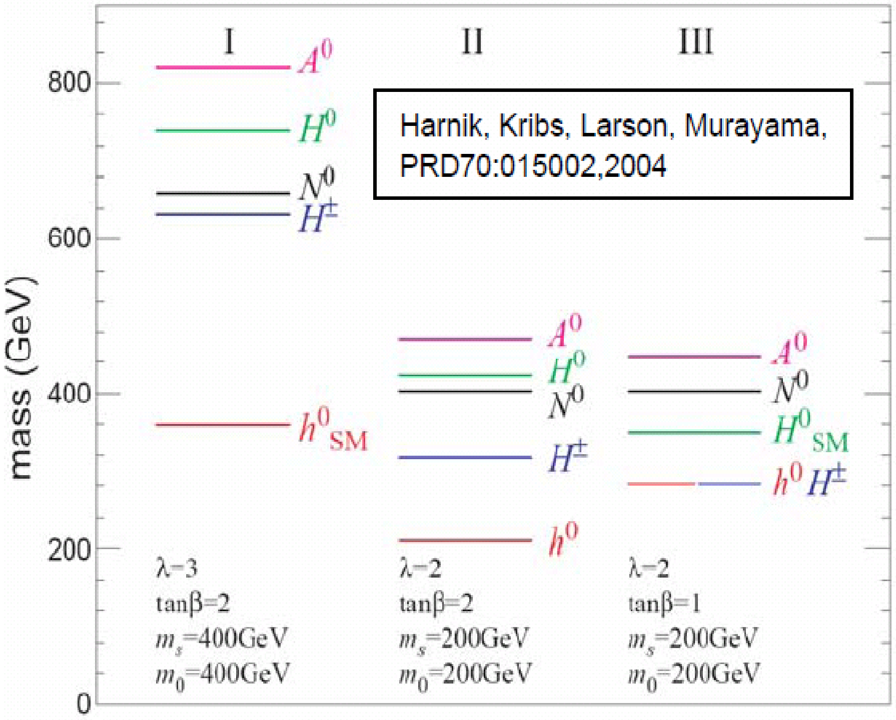
$$m_h^2 \simeq \lambda^2 v^2 + \mathcal{O}(m_Z^2)$$

$$M_{H^\pm}^2 = M_A^2 - \lambda^2 v^2$$

λ can be of O(1)

⇔ $m_h > 200$ GeV





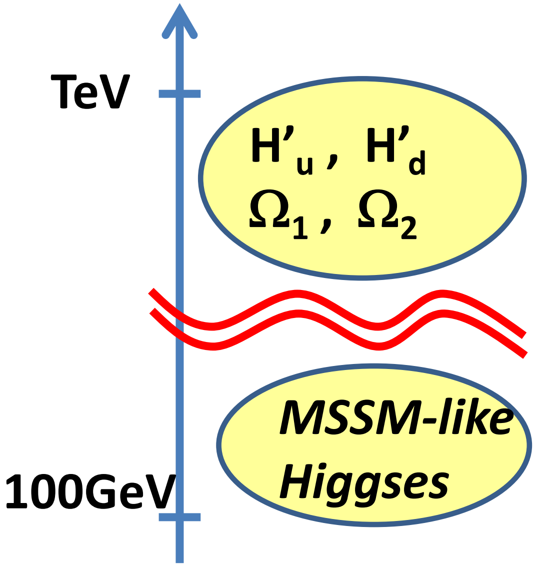
Harnik, Kribs, Larson, Murayama, PRD70:015002,2004

4HDM + charged singlets $\Omega_{1,2}$

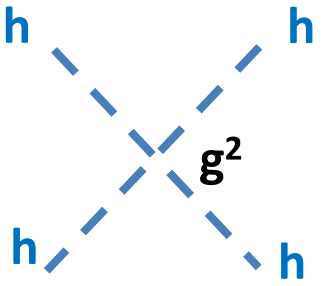
$H'_{u,d}$: extra doublets, $\Omega_{1,2}$: charged singlets

$$\boxed{W = \lambda_1\ H_u H_u' \Omega_1 + \lambda_2\ H_d H_d' \Omega_2}$$

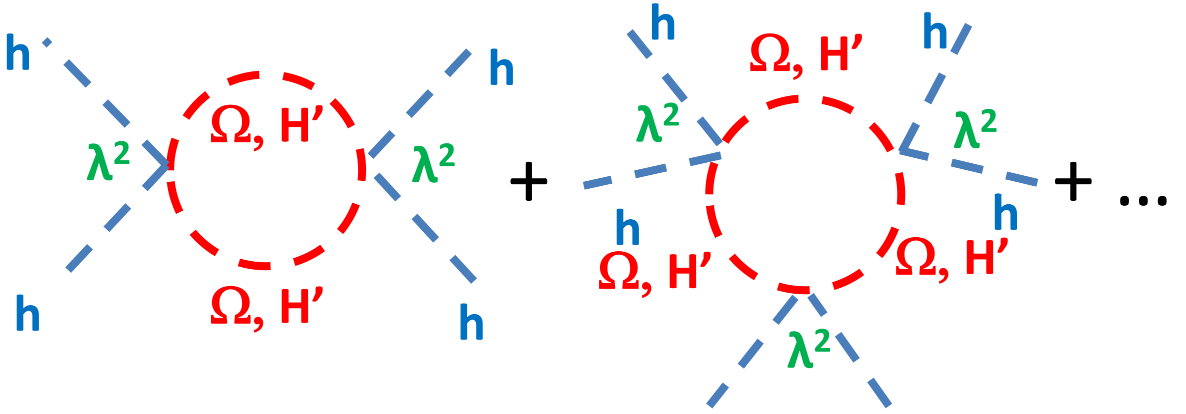
$$V_F = \lambda_1^{\,2}\ |H_u H_u'|^2 + \lambda_1^{\,2}\ |H_u \Omega_1|^2 + \lambda_1^{\,2}\ |H_u H_u'|^2$$
$$+\lambda_2^{\,2}\ |H_d H_d'|^2 + \lambda_2^{\,2}\ |H_d \Omega_2|^2 + \lambda_2^{\,2}\ |H_d\ H_d'|^2$$



No tree level contribution to the mass of *h*



One-loop contribution



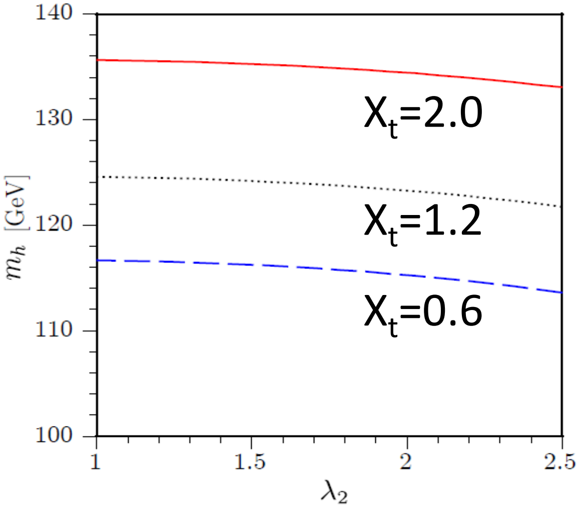
Non-decoupling effect appears in the *hhh* coupling after renormalization

Non-decoupling effects

SM-like Higgs mass

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + (\text{MSSM-loop}) + \frac{\lambda_1^4 v^2 c_\beta^4}{16\pi^2} \ln \frac{m^2_{\Omega_2^\pm} m^2_{\Phi_2'^\pm}}{m^4_{\bar{\chi}_2^\pm}} + \frac{\lambda_2^4 v^2 s_\beta^4}{16\pi^2} \ln \frac{m^2_{\Omega_1^\pm} m^2_{\Phi_1'^\pm}}{m^4_{\bar{\chi}_1^\pm}}$$

m_h cannot be very large: 114-135 GeV



The hhh coupling

$$\lambda_{hhh}^{\text{Model}} \simeq \lambda_{hhh}^{\text{SM}} \left[1 + \sum_{1,2} \frac{m^4_{\Omega_i}}{6\pi^2 v^2 m_h^2} \left(1 - \frac{\overline{m}_i^2}{m^2_{\Omega_i}} \right)^3 + \cdots \right]$$

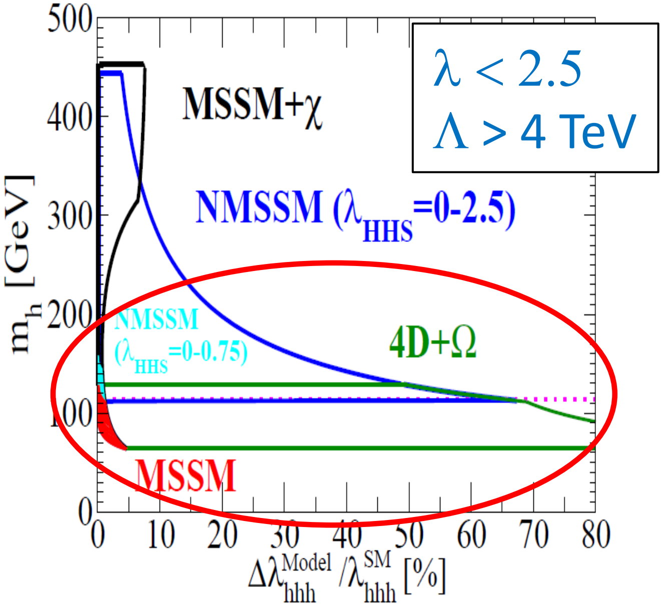
$$m^2_{\Omega_1} \simeq \overline{m}_1^2 + \frac{\lambda_1^2 \sin^2 \beta}{2} v^2$$

$$m^2_{\Omega_2} \simeq \overline{m}_2^2 + \frac{\lambda_2^2 \cos^2 \beta}{2} v^2$$

Deviation can be large when

$$m_{\Omega_i} \gg m_h$$
$$m_{\Omega_i} \gg \overline{m}_i$$

20-70% !



$\lambda < 2.5$

$\Lambda > 4$ TeV

Electroweak Phase Transition

Finite T potential

$$\boxed{V_{\rm eff}(\varphi_1,\varphi_2;T)=V_0(\varphi_1,\varphi_2)+V_1(\varphi_1,\varphi_2)+V_1(\varphi_1,\varphi_2;T)}$$

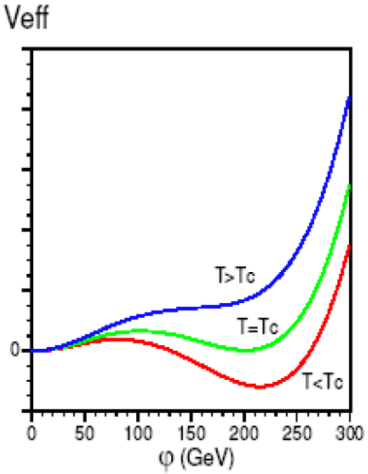
$$V_0(\varphi_1,\varphi_2)=\sum_{a=1}^{2}\frac{1}{2}\bar{m}_a^2\varphi_a^2+\frac{1}{2}(B\mu\varphi_1\varphi_2+\text{h.c.})$$

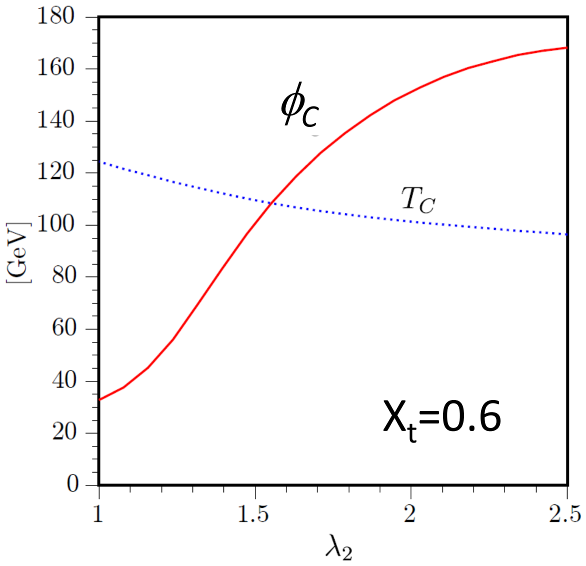
$$+\frac{g^2+g'^2}{32}(\varphi_1^2-\varphi_2^2)^2.$$

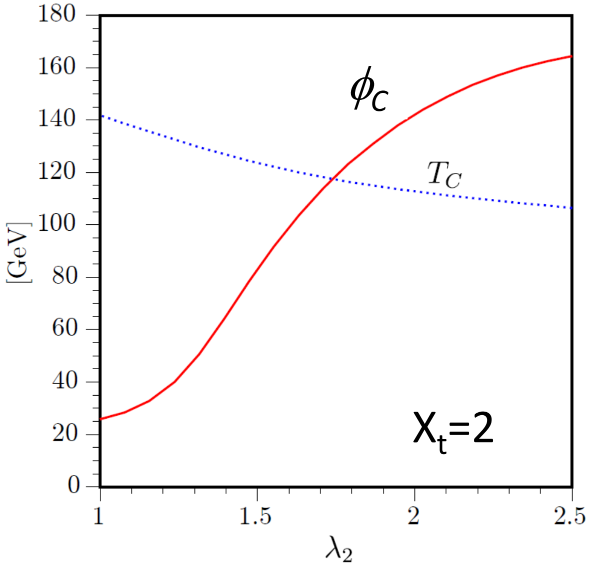
$$V_1(\varphi_1,\varphi_2)=\sum_i c_i\frac{\bar{m}_i^2}{64\pi^2}\left(\ln\frac{\bar{m}_i^2}{M^2}-\frac{3}{2}\right)$$

$$V_1(\varphi_1,\varphi_2;T)=\sum_i c_i\frac{T^4}{2\pi^2}I_{B,F}\left(\frac{\bar{m}_i^2}{T^2}\right)$$

$$I_{B,F}(a^2)=\int_0^\infty dx\ x^2\ln\left(1\mp e^{-\sqrt{x^2+a^2}}\right)$$







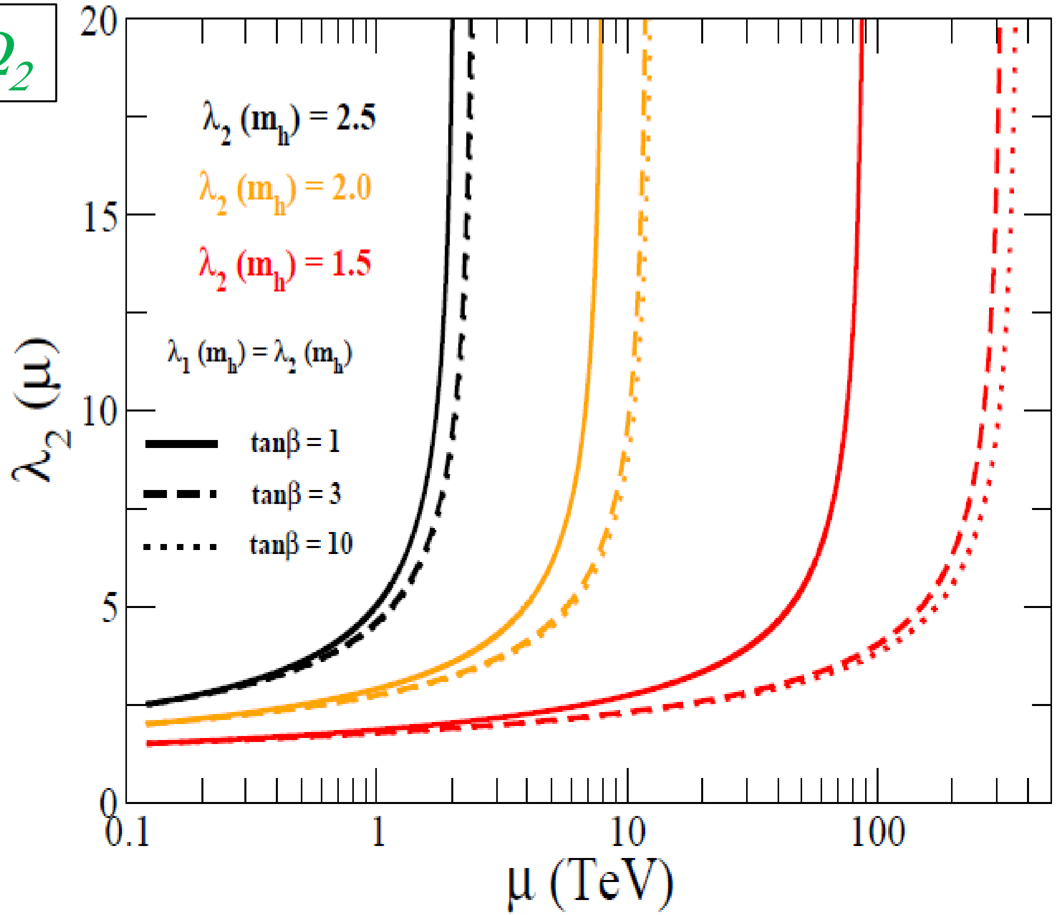
We numerically study ϕ_c (for each tanβ) and T_c for each parameter set of the model

There are regions of $\phi_c/T_c > 1$!

RGE analysis in 4HDM+Ω

$W = \lambda_1\ H_u H_u'\Omega_1 + \lambda_2\ H_d H_d'\Omega_2$

λ_2	Λ_{cutoff}
2.5	2 TeV
2.0	10 TeV
1.5	100 TeV



S.K., T. Shindou, K. Yagyu, 2010

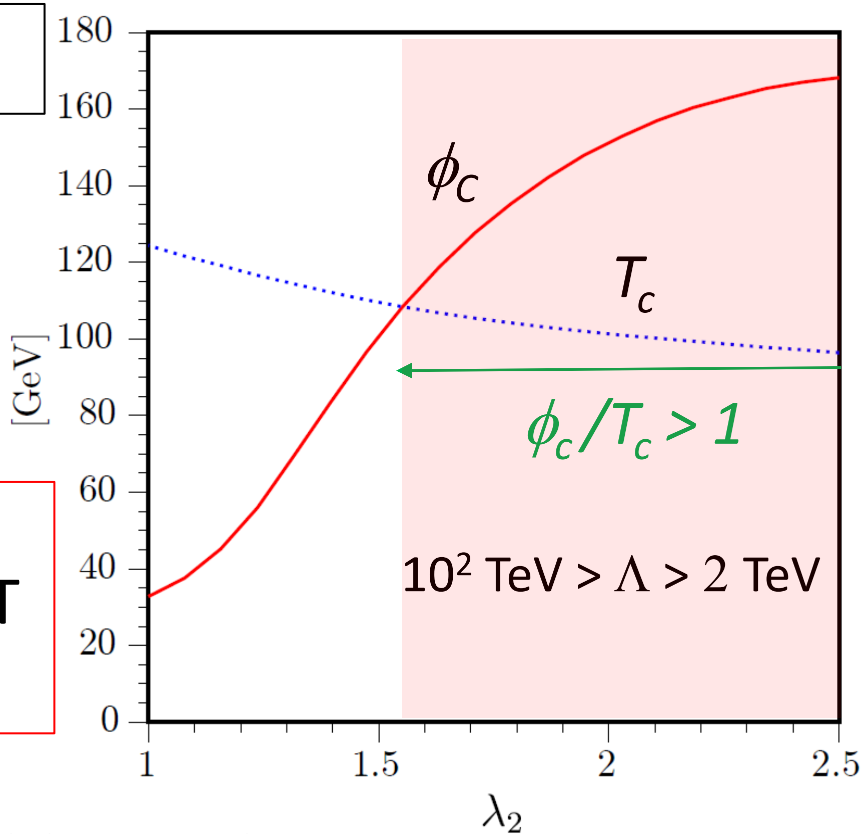
EW Phase Transition in 4HDM+Ω

S.K., E. Senaha, T. Shindou arXiv:1109.5226

$$\boxed{W = \lambda_1\ H_u H_u'\Omega_1 + \lambda_2\ H_d H_d'\Omega_2}$$

For relatively large λ_1, λ_2 couplings,

Sphaleron condition is satisfied



4HDM+Ω is a new viable model which can give the strong 1st OPT easily. (2 TeV < Λ_{cutoff} < 10^2 TeV)

In this case, deviations in the *hhh* coupling = 15% - 70 %

Large *hhh* coupling⇔ Strong 1st OPT

Testable at ILC !

Higgs self-coupling at ILC

The nature of EWSB $V(\phi)=-\mu^2|\phi|^2+\lambda|\phi|^4$

LHC: Difficult for a light
Higgs (< 140 GeV)

ILC: Testable

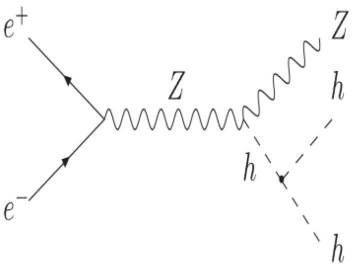
- Simulation study underway

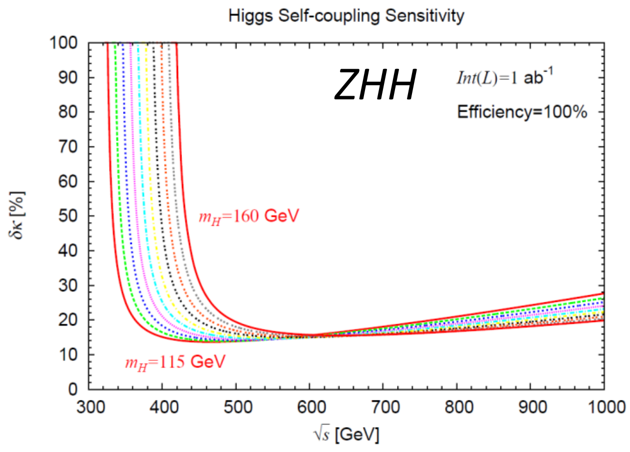
Suehara-san's talk

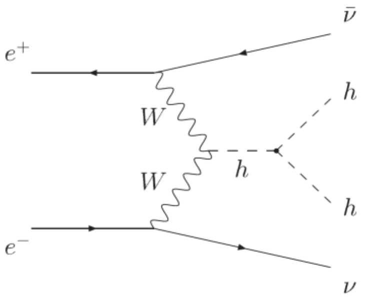
It is important to determine the hhh coupling by O(10) %

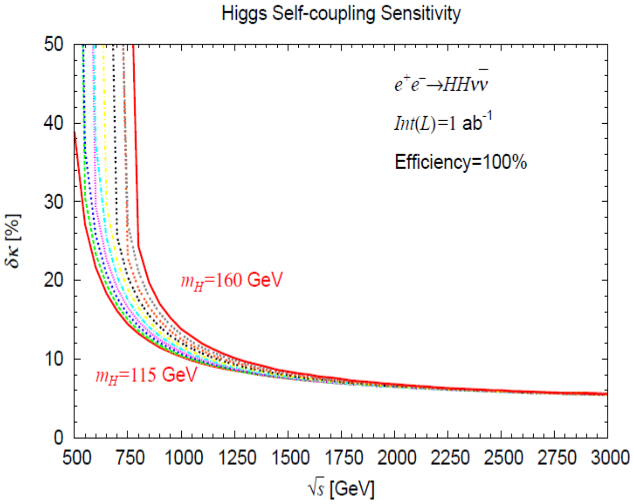
LC Physics!

Higs self-coupling sensitivity









D. Harada 2010

Summary

- We have discussed an extended SUSY Higgs sector which can naturally realize the strong 1st order phase transition

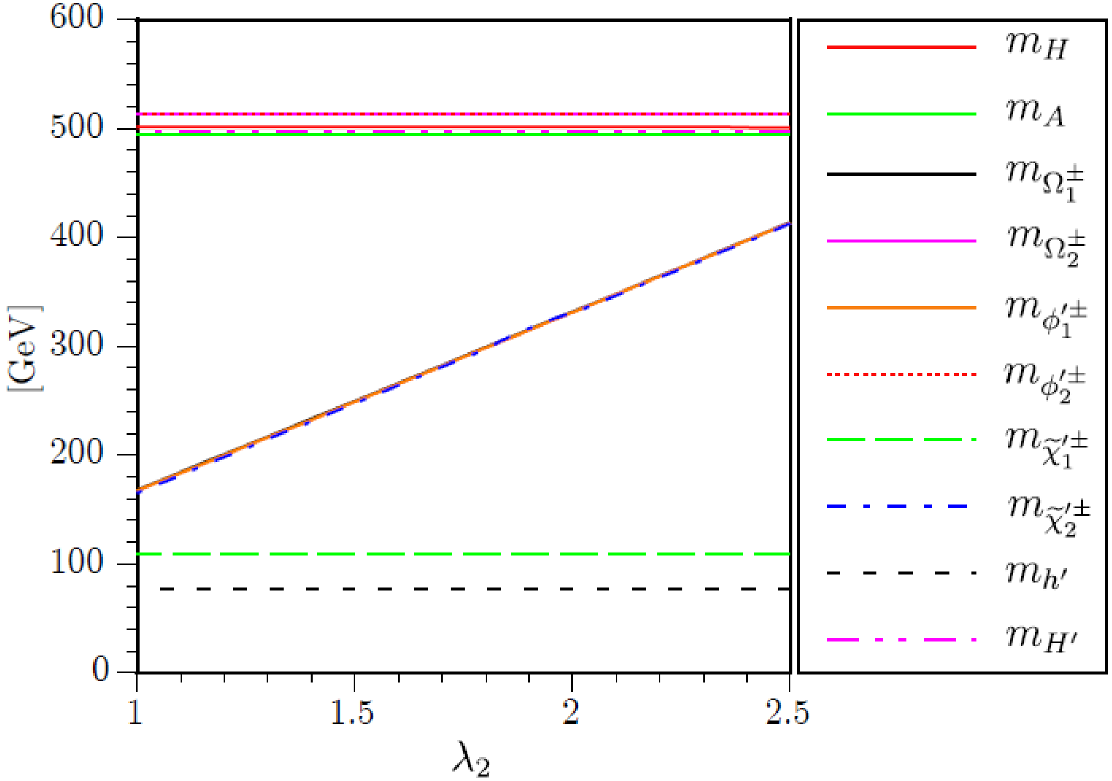
$$\boxed{W = \lambda_1 \; H_u H_u' \Omega_1 + \lambda_2 \; H_d H_d' \Omega_2}$$

- Relatively large λ_1, λ_2 couplings give significant non-decoupling contributions to the Higgs potential (1st OPT and the large deviation in the *hhh* coupling)
  - Strong coupled theory with a light SM-like Higgs boson

- The model can be a new candidate for successful EW baryogenesis

- The scenario can be tested by measuring the *hhh* coupling at the ILC (and light charginos)

Back up slides



$$\begin{aligned}
\text{Tree}: &\quad \tan\beta = 3,\ m_{H^\pm} = 500\ \text{GeV}; \\
\text{1-loop (MSSM)}: &\quad \tilde{M}_{\tilde{q}} = \tilde{M}_{\tilde{b}} = \tilde{M}_{\tilde{t}} = 1000\ \text{GeV}, \\
&\quad \mu = M_2 = 2M_1 = 200\ \text{GeV}, \\
&\quad A_t = A_b = X_t + \mu/\tan\beta; \\
\text{1-loop } (\Phi'^{\pm}_{1,2},\, \Omega): &\quad \lambda_1 = 2, \mu' = \mu_\Omega = B_\Omega = B' = 0, \\
&\quad \overline{m}_+^2 = \overline{m}_3^2 = (500\ \ \text{GeV})^2, \\
&\quad \overline{m}_-^2 = \overline{m}_4^2 = (50\ \ \text{GeV})^2.
\end{aligned}$$

Next-to-MSSM （NMSSM）

Two Higgs doublets H_u, H_d and a singlet S

$$\boxed{W = \lambda_{HHS} H_u . H_d S - \kappa S^3}$$

Mass of the lightest h in the NMSSM

$$m_h^2 \simeq m_Z^2 \underset{\substack{\uparrow \\ \text{D-term}}}{\cos^2} 2\beta + (\lambda_{HHS}^2 \underset{\substack{\uparrow \\ \text{F-term}}}{v^2}/2)\sin^2 2\beta + \delta m_{\text{loop}}^2$$

Ellwanger;
Kane, Kolda, Wells
………

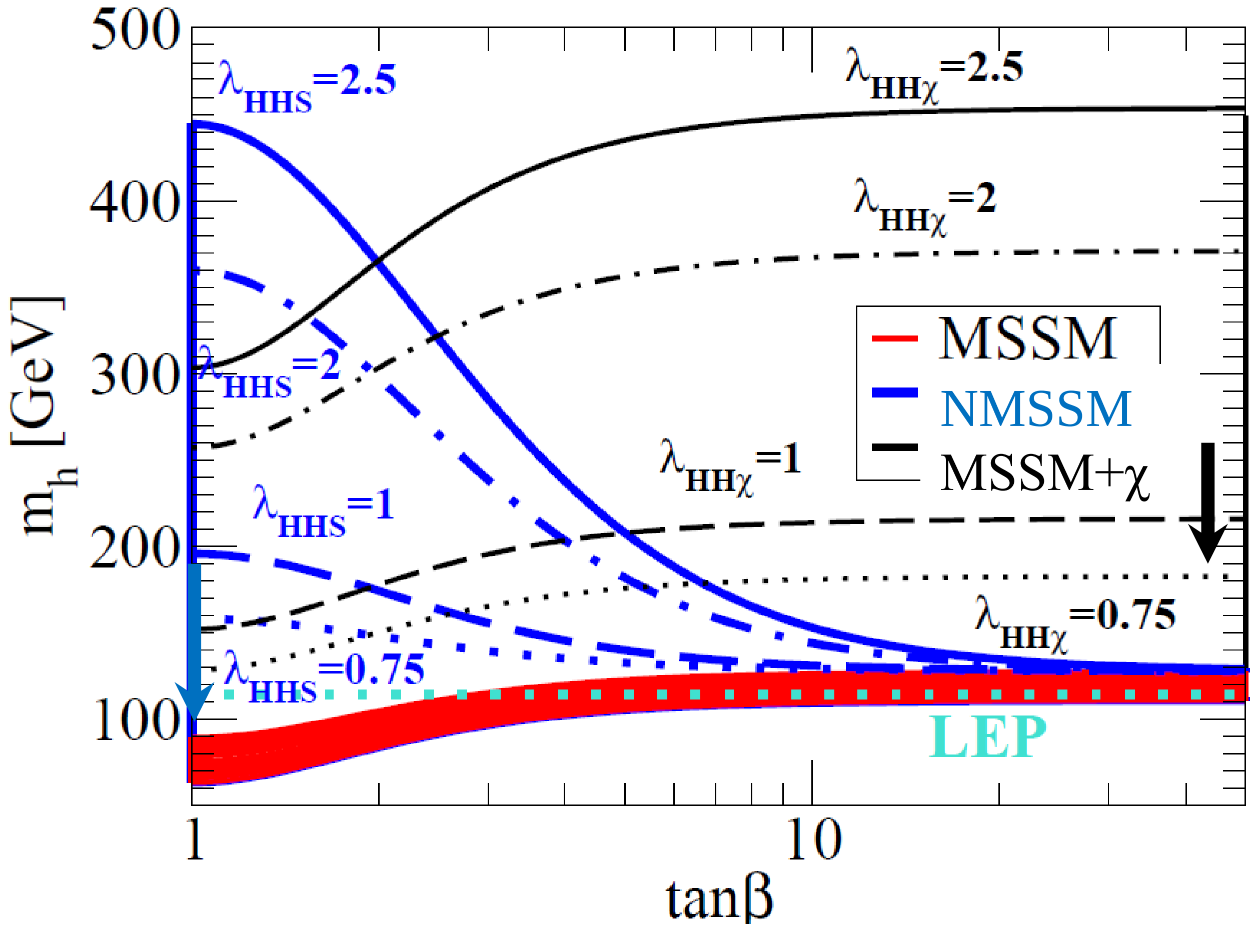
What is the size of λ_{HHS}?

RGE analysis with a cut-off scale Λ

Cut-off Λ : GUT scale → λ_{HHS} ~ 0.75 (m_h~ 140 GeV)

Cut-off Λ : TeV scale → λ_{HHS} ~ 2.5 (m_h~ 450 GeV)

Upper limit on m_h as a function of tanβ



Perturbative till GUT scale

Espinoza, Quiros '98,
.....

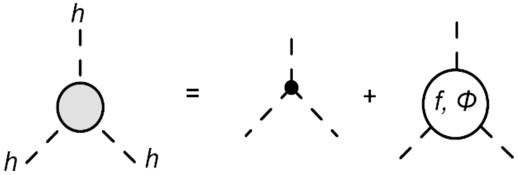
NMSSM
(singlet)

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \delta_{\text{loop}} + \frac{v^2}{2}\lambda_{HHS}^2 \underline{\sin^2 2\beta}$$

MSSM+χ
(triplet)

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \delta_{\text{loop}} + \frac{v^2}{2}\lambda_{HH\chi}^2 (\underline{\sin^4 \beta + \cos^4 \beta)}$$

The triple Higgs boson coupling



MSSM

Decouple!

$$\lambda^{\mathrm{MSSM}}_{hhh} \simeq \frac{3m_h^2}{v}\left[1-\frac{m_t^4}{\pi^2 v^2 m_h^2}\left\{1-\frac{m_t^2(m_{\tilde{t}_1}^2+m_{\tilde{t}_2}^2)}{2m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right\}\right]$$

NMSSM

Non-Decoupling effect!

$$\lambda^{\mathrm{NMSSM}}_{hhh} \simeq \frac{3m_h^2}{v}\left[1+\sum_{c=1}^{2}\frac{m_{S_c}^4}{12\pi^2 v^2 m_h^2}\left(1-\frac{M_{S_c}^2}{m_{S_c}^2}\right)^3\right]$$

$$m_{S_c}^2 \simeq M_{S_c}^2+\frac{\lambda_{HHS}^2}{2}v^2$$

Non-decoupling when

$$M_{S_c}^2 \lesssim \frac{\lambda_{HHS}^2}{2}v^2$$

Large tanβ ⇒ Small m_h ⇒ Large hhh deviation

Small tanβ ⇒ Large m_h ⇒ Small hhh deviation

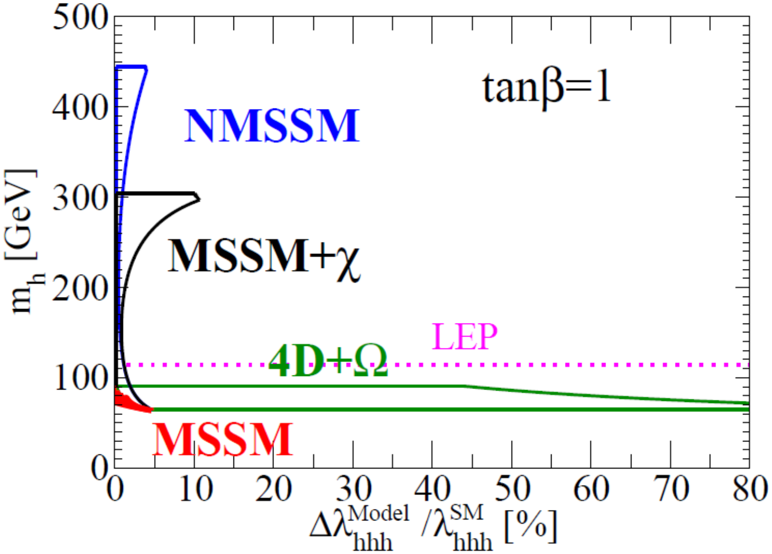
4HDM＋charged singlets

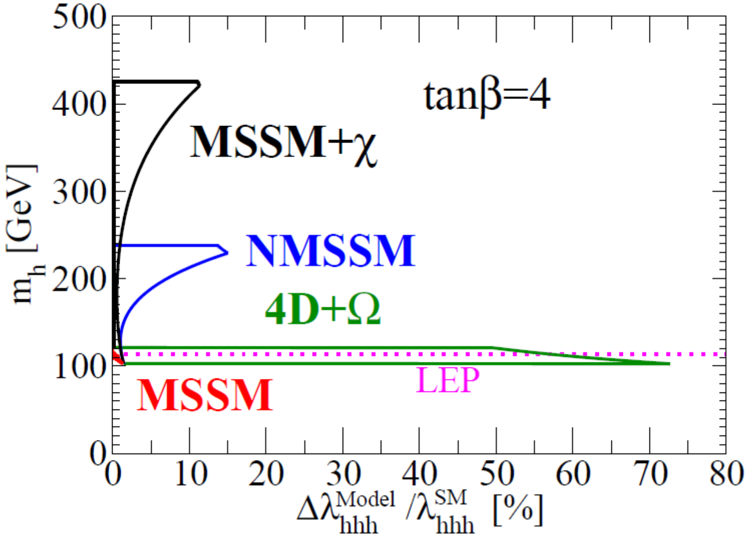
m_h determined by D-term

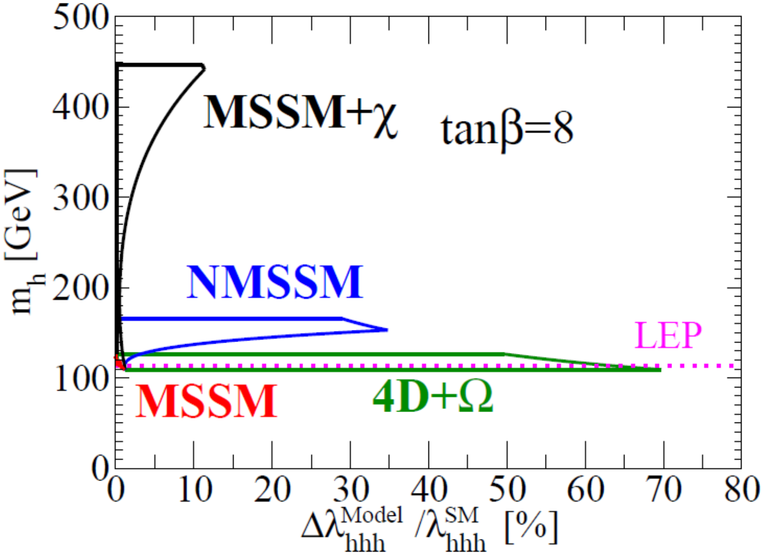
F-terms only contribute to hhh ⇒ Large hhh deviation

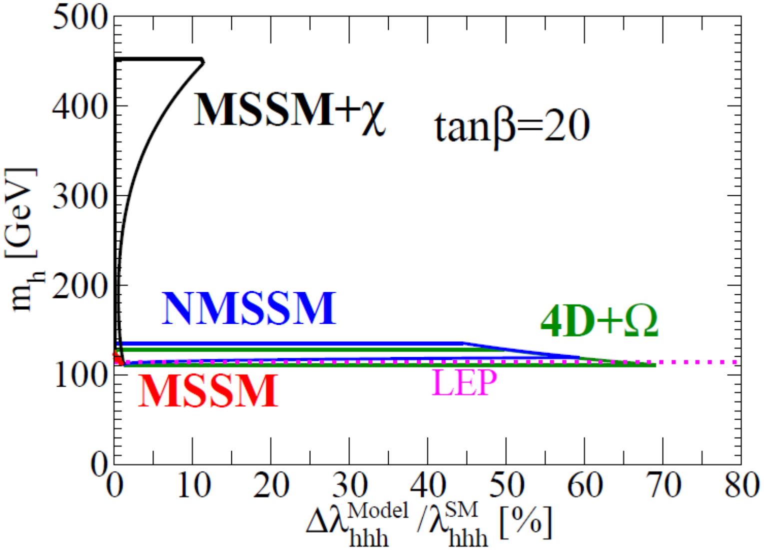
m_h-$\Delta\lambda_{hhh}$ plot for each tanβ

$\lambda < 2.5$
$\Lambda > 4$ TeV









m_h-$\Delta\lambda_{hhh}$ plot (tanβ = 1-50)